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Nuclear Rocket Propulsion
NASA Plans and Progress—FY 1991

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NUCLEAR ROCKET PROPULSION
NASA Plans and Progress - FY 1991

by

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ABSTRACT

NASA has initiated planning for a technology development project for nuclear rocket propulsion systems for Space Exploration Initiative (SEI) human and robotic missions to the Moon and to Mars. An Interagency project is underway that includes the Department of Energy National Laboratories for nuclear technology development. This paper summarizes the activities of the project planning team in FY 1990 and FY 1991, discusses the progress to date, and reviews the project plan.

Critical technology issues have been identified and include:
- Nuclear fuel temperature, life, and reliability
- Nuclear system ground test
- Safety
- Autonomous system operation and health monitoring
- Minimum mass and high specific impulse

NEP AND NTP WORKSHOPS

In June and July, 1990, NASA sponsored workshops on Nuclear Electric Propulsion (NEP) [1] and Nuclear Thermal Propulsion (NTP) [2], respectively. Many nuclear propulsion concepts were presented. The concepts were compared with a reference system [3] (Table 1) for the manned mission to Mars in 2016, to identify technology development requirements and facility requirements for the concept, and to estimate a development schedule and cost. Panels of technical experts assessed the concepts [4] based on:
- potential mission benefit (performance)
- safety
- technology needs and risk
- development schedule and cost

Figure 1 is a schematic diagram of a nuclear electric vehicle with the reactor (R) and shield (S) on the left, and payload and thrusters on the right, with radiators, power conversion and power conditioning equipment in between. A relatively clean interface exists between the power generation sub-systems and the propulsion (thruster) sub-systems. The electrical power is used to accelerate ions or other sub-atomic particles, resulting in continuous low thrust.

Table 2 lists the concepts presented at the NEP workshop. Ten power concepts and nine propulsion concepts were presented. Solid and gaseous fuel nuclear reactors were included, with both liquid metal and gas cooling. Thermal-to-electric power conversion included dynamic (Rankine, Brayton) and static (thermionic, HYTEC). Propulsion concepts included steady state and pulsed electromagnetic engines, a pulsed electrothermal engine, and a steady state electrostatic engine.

Figure 2 is a schematic diagram of a solid core nuclear thermal engine. Hydrogen is heated inside the reactor core and expanded through the nozzle to produce thrust. Table 3 summarizes the concepts presented at the NTP workshop. Nine solid core concepts were presented including: homogeneous thermal - NERVA (the reference concept - circa 1970), an upgraded NERVA - ENABLER; a heterogeneous reactor - the particle bed; and fast reactors - cermet and wire core. Liquid core concepts and gaseous core concepts were also presented. A NIMF concept was presented that used in-situ propellant (CO_2), and dual mode concepts were presented.

The technical panels reported to an Interagency Steering Committee, and their recommendations formed the basis for the FY 1991 plans for the project:

(1) Develop a consistant basis for comparing nuclear propulsion concepts
(2) Assess facility requirements
(3) Prepare draft safety policy
(4) Optimize missions for nuclear propulsion
(5) Develop Interagency Agreements
(6) Complete and approve Project Plan
(7) Prepare initial SOW's
(8) Initiate public acceptance planning

FY 1991 ACTIVITIES

Interagency project teams were formed in FY 1991 to act upon these recommendations, to continue to improve the project plans and to initiate some critical technology development, in spite of very limited funding for the project in FY 1991. Teams were formed in each of the following areas:

- Mission Analysis
- NTP Technology
- NEP Technology
- Nuclear Fuels and Materials Technology
- Nuclear Safety
- Test Facilities

Figure 3 presents a plan for the FY 1991 panel activities. The Nuclear Safety Policy Working Group is reviewing NASA and Department of Energy safety policy and will recommend an appropriate Interagency policy for the Project. Some of the issues that are being addressed include:

- astronaut-rating requirements
- inadvertant reentry (subcriticality, impact)
- redundancy requirements
- probabalistic risk
- fission product release
- operational safety
    - ground testing
    - launch
    - reactor startup and flight
- safety validation requirements
- disposal criteria

The Mission Analysis team is developing consistent nuclear propulsion reference scenarios, assessing mission operations and abort scenarios, and quantifying the benefits of expected nuclear propulsion mission options.

The NTP technology Panel is preparing test and development needs for a wide range of NTP concepts, to provide guidance for the technology development plan. The NTP Technology Panel is also evaluating the NTP concepts based on a consistent set of technology levels: solid fuel temperatures of 2700 K, 2900 K, 3100 K, for example, and appropriate projections of liquid and gas core temperatures from 4000 to perhaps as high as 15,000 K. A consistent set of non-nuclear technologies will be included for pumps, nozzles, shielding, and so forth, in order to fairly compare the concepts for the SEI missions. Proof-of-Concept (POC) experiments will be defined for the more innovative, high pay-off concepts, and a portion of the project funding is planned to continue to evaluate and develop these high performance systems.

An NEP Technology Panel will also use common ground rules and assumptions for an initial comparison of system-level options and combinations of reactor types and thrusters. Instrumentation, neutronics and controls technologies are included in both the NTP and the NEP panels, and will be incorporated in the systems development from the inception.

Similarly, a Nuclear Fuels and Materials Technology Panel is assessing fuels and materials development plans. Fuels development was agreed to be one of the most important technologies to be developed, and will be a major focus of the effort early in the program.

The Test Facilities Planning Team has reviewed test requirements provided by the technology panels, evaluated existing facility capabilities, and will recommend facility modifications and new facility requirements. Reactor and thruster facilities will be required for the NEP technology development. A nuclear furnace (a facility to test reactor elements in a nuclear, hydrogen-cooled environment), a full reactor test facility, and a full NTP system (including tank, pumps, nozzle, reactor and control systems) will be required for NTP development. A full effluent cleanup system will be required for these facilities to ensure negligible environmental impact at the test site.

NUCLEAR PROPULSION PROJECT PLAN

A draft Project Plan was prepared in parallel with the workshops in FY 1990, has been updated in FY 1991 with the input from the technical panels and working groups, and is currently proceeding through the Interagency approval cycle. In parallel, Memoranda of Agreements are proceeding between the agencies that will define management policies and procedures. The project plan (Figures 4 and 5) includes evolutionary technology development for both nuclear electric propulsion systems and nuclear thermal propulsion systems.

The NEP development uses the SP-100 technology, being developed for spacecraft power (and may be applied to Lunar and Mars surface nuclear power), as a foundation from which to develop more powerful, lighter systems for interplanetary probes, lunar and Mars cargo vehicles, and lunar and Mars human-piloted vehicles.

Similarly, the NTP technology development plan utilizes the substantial NERVA data base developed in the 1960's and early 1970's for solid core thermal reactors, and includes other advanced concepts with improved nuclear fuels to permit higher operating temperatures and longer life, and ultimately, to upgrade the system to liquid or gaseous core concepts. Thus, a logical, step-wise evolutionary project is planned that will have systems ready for initial unmanned lunar system flights by about 2010, will include robotic lunar missions to gain operational experience prior to manned flight, and will then proceed to manned lunar missions to simulate a fullup Mars mission, except in respect to the distance from the Earth. Mars robotic missions are planned to begin in about 2012, with the first manned Mars mission in about 2016. Innovative technology development is included in the project plan to ensure that system upgrades can evolve that will result in shorter trip times or improved payload capabilities.

A significant effort is planned to foster public acceptance for SEI nuclear propulsion systems. The major technology development activities will be guided by conceptual design and systems engineering studies. Thus, technology tasks will be focussed on appropriate development leading to improved components and systems. Innovative concepts will be included in the plan to ensure that advanced concepts are developed in a timely manner for second or third generation nuclear systems. Last, but certainly not least, safety, quality assurance, reliability, risk management and environmental concerns will be included as a major component of each task in the project.

SUMMARY

In summary, a nuclear propulsion program is underway at NASA, with significant DOE nuclear technology development, to provide a nuclear vehicle for SEI Lunar and Mars missions. The project includes both NTP and NEP systems, and is evolutionary. A significant NTP technology base exists from the NERVA program; no major engineering hurdles remain for nuclear thermal propulsion systems. More development will be required for nuclear electric systems, especially for manned NEP systems to be competitive based on trip time, but NEP offers long-term advantages because of its inherent high specific impulse. Innovative concepts will also be studied to provide even faster trip times and cost advantages.

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The authors wish to acknowledge the guidance and support provided (on a non-reimbursed basis) by the technical panels and working groups in 1991. Their input in the planning process has been most helpful, their enthusiasm for nuclear propulsion is contagious, and the friendships that have developed, we hope will be long-lasting.

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[1] J.W. Barnett, "Proceedings of the NASA/DOE/DOD Nuclear Electric Propulsion Workshop," held in Pasadena, CA, June 19-22, 1990, JPL CP-______, 1991

[2] J.S. Clark, "Proceedings of the NASA/DOE/DOD Nuclear Thermal Propulsion Workshop," held in Cleveland, OH, July 10-12, 1990, NASA CP-______, 1991

[3] T. J. Miller, J.S. Clark, and J.W. Barnett, "Nuclear Propulsion Project Workshop Summary," AIP CONF- 910116, Proc. Eighth Symposia on Space Nuclear Power Systems, Part I, pp. 84-92, Jan., 1991

[4] J.S. Clark, "A Comparison of Nuclear Thermal Propulsion Concepts: Results of a Workshop," AIP CONF-910116, Proc. Eighth Symposia on Space Nuclear Power Systems, Part II, pp. 740-748, Jan., 1991

TABLE 1.- NUCLEAR PROPULSION WORKSHOP REFERENCE SYSTEM

MISSION:
MANNED MISSION TO MARS
LAUNCH IN 2016
ENGINE AVAILABLE IN 2015
OUTBOUND MASS – 124 mt
DEPLOYMENT ORBIT: SSF, 407 km
RETURN MASS – 40 mt
< 600 DAY MISSION
30 DAY STAY ON MARS
< 5 REM/YR – REACTOR TO CREW
NTP SYSTEM (NERVA–1970):
THRUST: 75,000 lb (334 kN)
SINGLE ENGINE
REACTOR THERMAL POWER: 1500 MW
T/W (w/o SHIELDING): 4
SPECIFIC IMPULSE: 850 SECONDS
NOZZLE: 100:1
SINGLE TRIP
REACTOR OPERATING TIME: 2 HR.
STARTUP CYCLES: 6
MISSION DURATION: 434 DAYS
NEP SYSTEM:
POWER: 10 MWe
SPECIFIC MASS: < 10 kg/kWe
NO. OF MISSIONS: 3
STARTING CYCLES: 15
MISSION DURATION: 550 DAYS
ION THRUSTER:
SPECIFIC IMPULSE: 6000 SECONDS
EFFICIENCY: 50%
LIFE: 10,000 HOURS
POWER CONVERSION SYSTEM:
POTASSIUM RANKINE
POWER PROCESSING UNIT:
EFFICIENCY: 95%
TEMPERATURE: 600 K

TABLE 2.- NEP CONCEPTS PRESENTED TO THE NEP WORKSHOP

POWER CONCEPTS

Focal Point	Organization	Concept
P. Pluta	General Electric	SP-100 Scale-up
B. Pierce	Westinghouse	ENABLER (NERVA-based)
J. Powell	Brookhaven Nat'l. Lab.	Particle Bed Reactor
M. El-Genk	U. of New Mexico	Pellet Bed Reactor
C. Walter	Livermore Nat'l. Lab.	10 MWe Nuclear Rankine System
J. Mills	Rocketdyne	Potassium Rankine System
B. Reid	Pacific Northwest Lab.	TORCHLITE (Thermionic System)
T. Van Hagan	General Atomics	In-core Thermionic System
N. Diaz	U. of Florida	Vapor Core Reactor
P. Turchi	Ohio State U.	NEPTUNE (NERVA-based)
B. Johnson	Pacific Northwest Lab.	RMBLR*

PROPULSION CONCEPTS

Focal Point	Organization	Concept
R. Myers	Sverdrup/LeRC	MPD Thruster
P. Turchi	Ohio State U.	NEPTUNE (NERVA-based)
D. Cheng	Cheng Technologies	Deflagration Thruster
R. Bourque	General Atomics	Pulsed Plasmoid Thruster
R. Burton	U. of Illinois	Pulsed Electrothermal Thruster
J. Beattie	Hughes	Ion Engine
J. Sercel	JPL	Electron Cyclotron Resonance
T. Karras	General Electric	Ion Cyclotron Resonance
C. Dailey	TRW	Pulsed Inductive Thruster
F. Chang-Diaz	NASA/JSC	Variable Isp Plasma Rocket*

* Submitted after the Workshop

TABLE 3.- COMPARISON OF NTP WORKSHOP RESULTS

			PERFORMANCE PARAMETERS				
CONCEPT:	CO./CFP	TRL	Isp (Sec)	TRIP TIME, (DAYS)	IMLEO, (Klb)	FUEL	TEMP. (K)
SOLID CORE:							
NERVA BASELINE*	—	6	825–850	434	884	DUPLEX	2270
ENABLER	W/FARBMAN	4–5	925–1080		713	UC–ZrC–C	2700–3300
CERMET*	GE/KRUGER	4–5	832			UO2/W	-
WIRE CORE	RI/HARTY	2	930			UN/W	3030
ADV. DUMBO	LANL/KIRK	3–4	-			UC/ZrC	2700–3300
PELLET BED	NM/EL-GENK	3	998			UC/TaC	3100
PARTICLE BED	BNL/LUDEWIG	4	1000–1200	434	660	UC/ZrC	3000–3500
LOW PRESSURE	INEL/RAMS.	1–2	1050–1210		814–534	UC/ZrC	3000–3600
FOIL REACTOR	SNL/WRIGHT	1–2	990		992	UO2	2700/3400
LIQUID CORE:							
LIQUID ANNULUS	BNL/LUDEWIG	1	1600–2000			?	3000–5000
DROPLET CORE	FL/ANGHAIE	1–2	1500–3000	<200	600	?	5000–7000
GASEOUS CORE:							
OPEN CYCLE	SV/RAGSDALE	1–2	5200	60–80		U PLASMA	?
VAPOR CORE	FL/DIAZ	1–2	1280	310		UF4–HfC	6000–8000
LITE BULB	UTRC/LATHAM	1–2	1870			?	7200
OTHER CONCEPTS:							
NIMF (@)	MM/ZUBRIN	1	283	-	50% LESS	Th/UO2/Zr	2800
DUAL-MODE	+	+	+	+	+	+	+

* - 1960'S TECHNOLOGY

@ - INSITU RESOURCE UTILIZATION CONCEPT

+ - SEVERAL SPEAKERS ADDRESSED DUAL MODE CONCEPTS

FIGURE 1.- NEP VEHICLE/SYSTEM SCHEMATIC

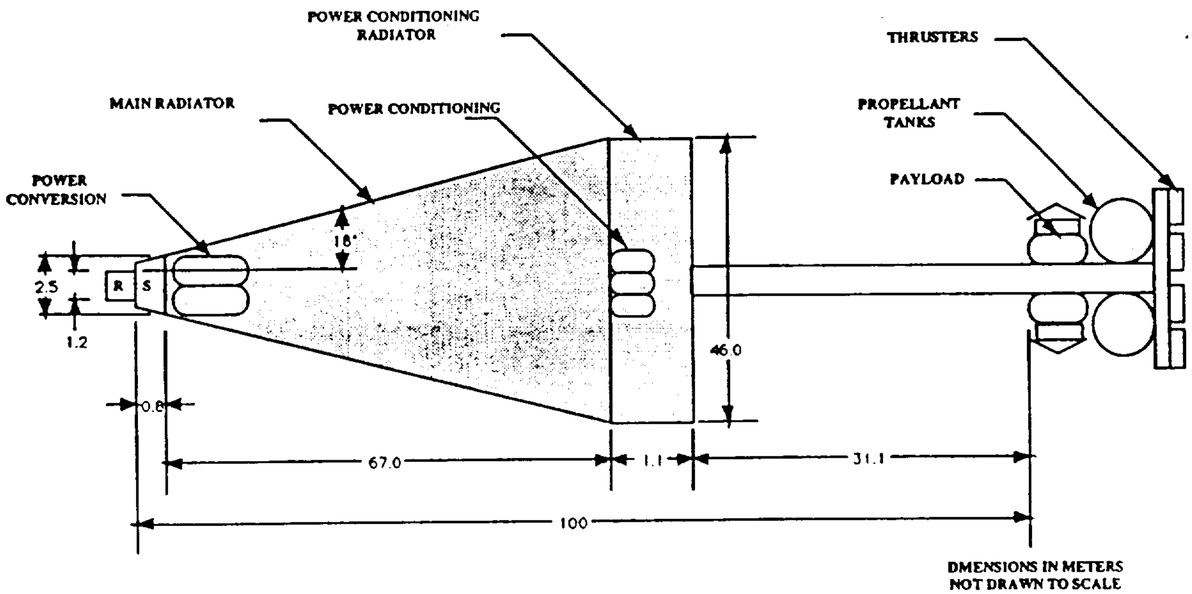


FIGURE 2.- NTP SOLID CORE SCHEMATIC DIAGRAM

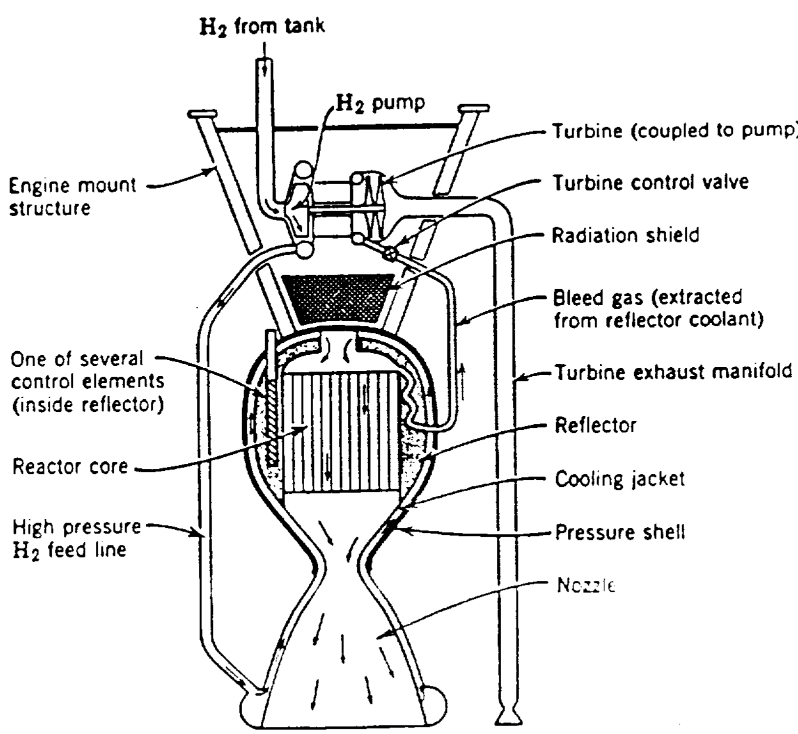


FIGURE 3. - TECHNICAL PANELS/WORKING GROUPS PLAN

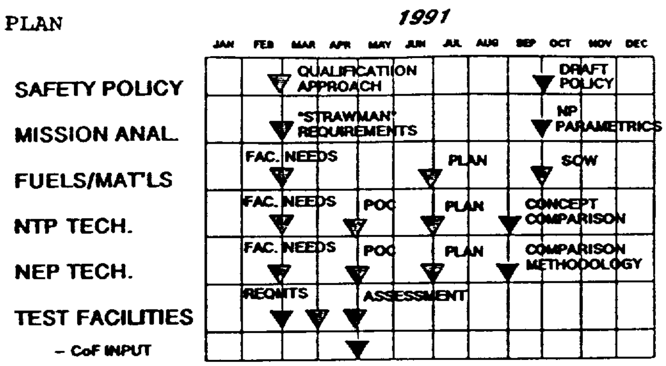


FIGURE 4.- NUCLEAR PROPULSION PROJECT IS EVOLUTIONARY

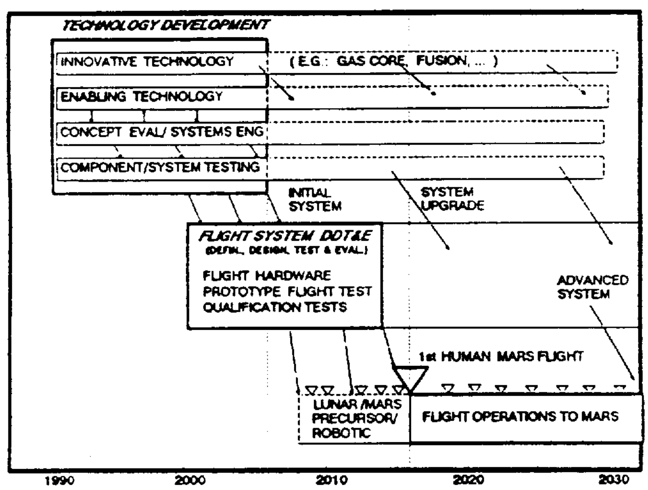
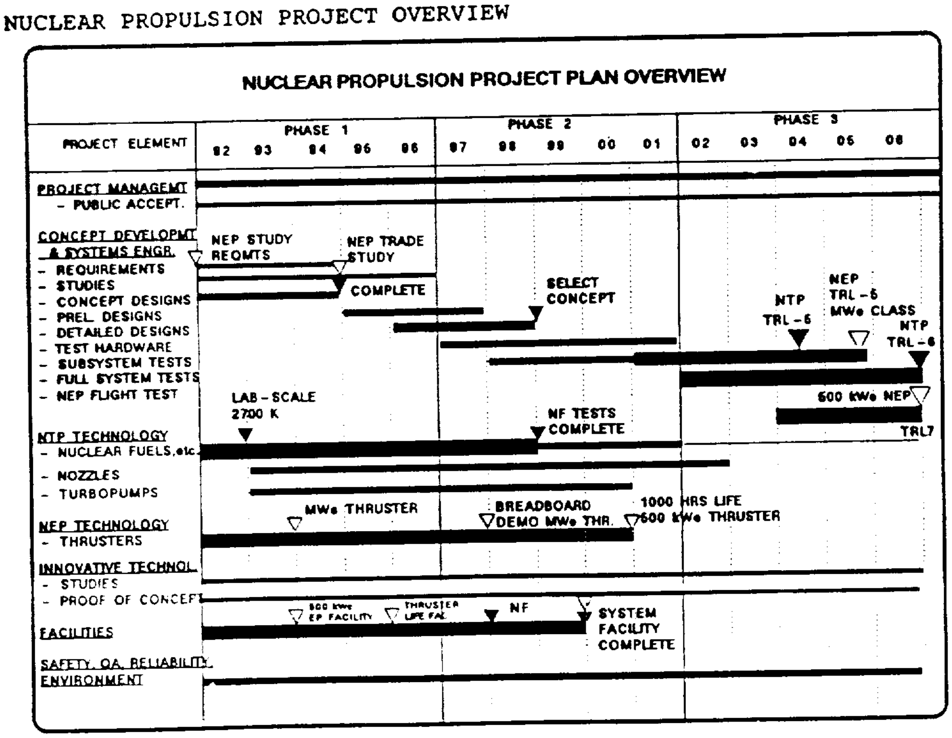


FIGURE 5.- NUCLEAR PROPULSION PROJECT OVERVIEW



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